Dean&Francis
ISSN 2959-6157

Applications for PID Control DC Motors in All-terrain Robots: Theory and Practice

Yunqi Wang[1, *]

[1]Department of Electronic and Electrical Engineering, University of Liverpool, Liverpool, L69 7ZX, The United Kingdom
[*]sgywa87@liverpool.ac.uk

Abstract:

This article proposes a control strategy based on dual-loop PID for the motion control of all-terrain mobile robots in complex environments. The research combines theoretical analysis and practical verification to design and implement an innovative dual-loop control system. The experimental platform adopts a spherical all-terrain robot, which achieves all-round motion control through a three-wheel omnidirectional drive structure. The system integrates a balancing loop based on PD control and a speed loop based on PI control, achieving the unity of motion stability and accuracy. The experimental results show that the optimized control system has a steady-state error of less than 1%, a response time of 150ms, and an external disturbance recovery time of no more than 0.5s. The system exhibits excellent adaptability under various terrain conditions and can adapt to a maximum tilt angle of 15 degrees. This study provides a practical solution for high-performance motion control of all-terrain mobile robots and has important reference value for developing autonomous robot systems.

Keywords: All-terrain mobile robot; Dual-loop PID control; Stability control of movement; Real time parameter optimization; DC motor control

1. Introduction

With the rapid development of robotics technology, the application of all-terrain mobile robots in industrial, military, and civilian fields is becoming increasingly widespread [1]. However, achieving stable and reliable motion control still faces many challenges, especially in complex terrain environments. Ensuring the motion accuracy and balance of robots has become a key issue that urgently needs to be addressed.

Traditional PID control is widely used in robot control systems due to its simple structure and high reliability [2]. However, in all terrain application scenarios, a single PID control often fails to meet the dual requirements of stability and maneuverability for the system. In recent years, scholars both domestically and internationally have conducted extensive research on this topic. However, there are still problems in existing research such as insufficient control accuracy and limited anti-interference ability [3].

This article proposes a novel dual-loop PID control strategy, which achieves high-precision motion control of all-terrain robots through the coordinated cooperation of the inner and outer loops. The design includes a balance loop based on PD control and a speed loop based on PI control, effectively solving the balance problem between stability and tracking accuracy; Innovative parameter optimization methods have been proposed, significantly improving the dynamic performance of the system; And through practical platform verification, the practicality of this method in complex environments has been proven.

2. Methodology

2.1 Construction of Mathematical Model for DC Motor

In the all-terrain robot system, the DC motor serves as the core actuator, and the accurate establishment of its mathematical model is the foundation of control system design. The DC motor system used in this study can be described as a coupled electrical mechanical system. According to Kirchhoff's law of voltage and Newton's law of motion, the dynamic characteristics of a system can be described by two subsystems: electrical and mechanical. In the modeling process, as shown in Fig. 1, the modeling process fully considered the mutual influence between the electrical and mechanical characteristics, which is crucial for the design of the subsequent control system.

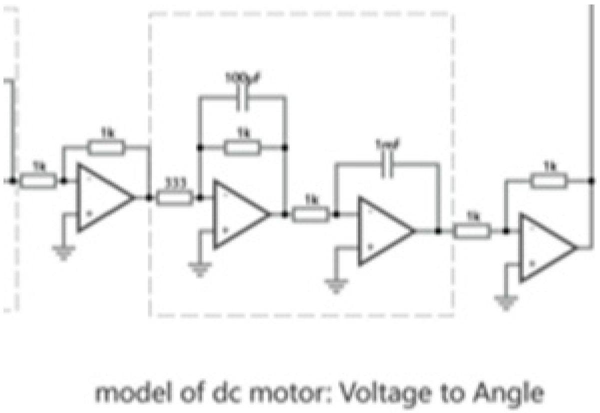

Fig. 1 Model of DC motor: Voltage to angle. (Picture/Photo credit: Original)

$$dx/dt = Ax + Bu \quad (1)$$

$$y = Cx + Du \quad (2)$$

where state variable x includes motor speed and current, input u is the applied voltage and output y is the actual speed.

In terms of kinematic analysis, as shown in Fig. 2, the system adopts a three-wheel omnidirectional drive structure and establishes a mapping relationship between wheel speed and robot speed through precise geometric relationships. This structure, as shown in Fig. 3, has unique motion characteristics, enabling the robot to achieve all-round motion control. By establishing forward kinematics equations, The equations accurately describe the motion state of the robot:

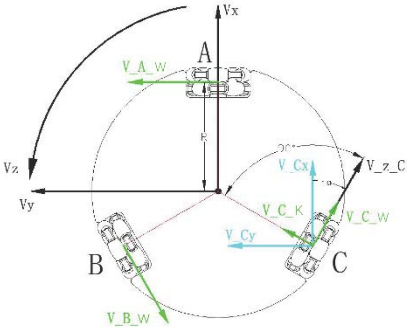

Fig. 2 Schematic diagram of movement. (Picture/Photo credit: Original)

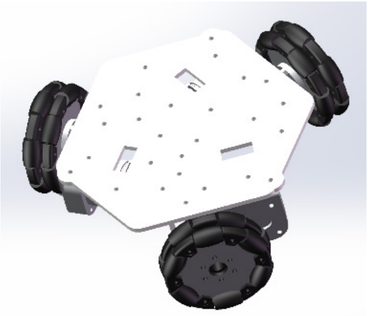

Fig. 3 Technical validation chassis. (Picture/Photo credit: Original)

$$v_x = \frac{V_C - V_B}{\sqrt{3}} \quad (3)$$

$$v_y = \frac{2V_A - V_B - V_C}{3} \quad (4)$$

$$v_z = \frac{V_A + V_B + V_C}{3R} \quad (5)$$

The various parameters reflect the physical characteristics of the system, and the establishment of this mathematical model provides a reliable theoretical basis for the design of subsequent control systems.

2.2 Design and Parameter Optimization of PID Controller

This study adopted an innovative dual-loop PID control strategy, which fully considers the dual requirements of balance, as shown in Fig. 4, and speed control, as shown in Fig. 5, for all-terrain robots in practical applications [4]. The control architecture of the system includes two parts: inner loop balance control and outer loop speed control, which work together, as shown in Fig. 6, to ensure the overall performance of the robot [5].

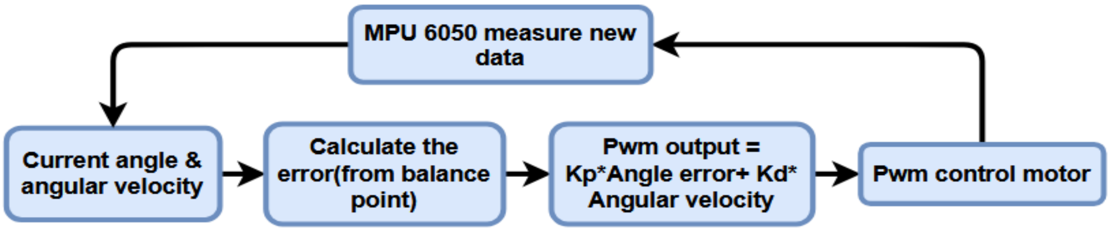

Fig. 4 Operating principle of balance loop control. (Picture/Photo credit: Original)

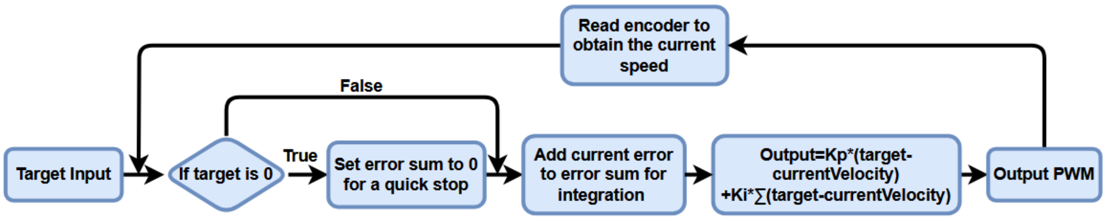

Fig. 5 Operating principle of velocity loop control. (Picture/Photo credit: Original)

In the balance control phase, the main consideration for adopting a PD control strategy is that balance control requires a fast response, while the integral term may lead to a slow system response. Through actual testing, it has been found that static error is not the main consideration factor in balance control, and the rapid response and stability of the system are more important. The design of the PD controller follows the following principles: first, establish the basic control strength through proportional terms, and then provide necessary damping through differential terms to suppress possible oscillations in the system [6].

The speed control link adopts PI control, which is based on the requirement of steady-state accuracy for speed control. In practical applications, it was observed that speed control requires the elimination of steady-state errors, so introducing an integral term is necessary. The specific implementation of the controller adopts strategies such as integral limiting and low-pass filtering to improve the system's robustness. An effective parameter adjustment method was determined through repeated experiments and optimization to ensure optimal control performance.

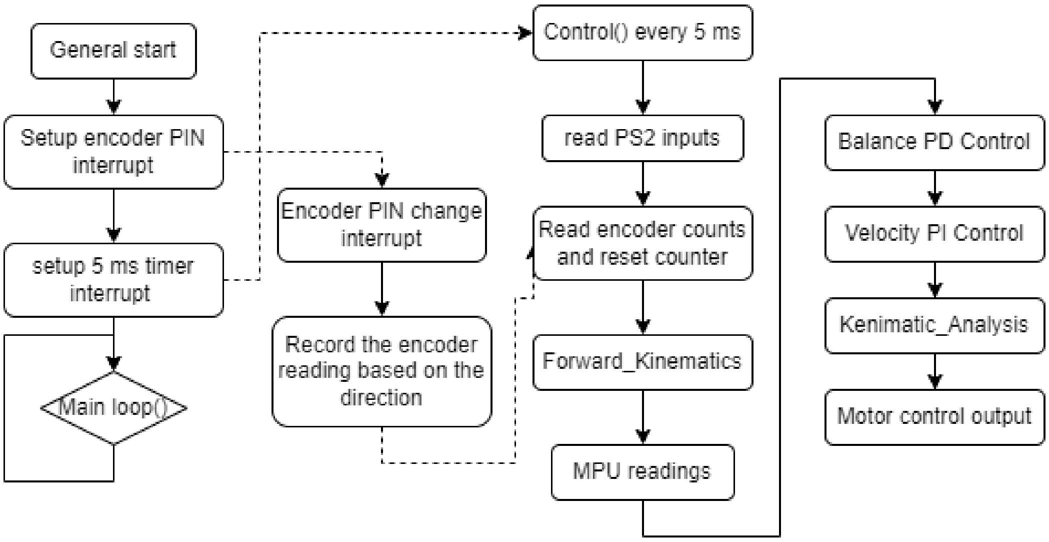

Fig. 6 General structure of the control system. (Picture/Photo credit: Original)

2.3 System Simulation and Experimental Platform Construction

The design of the experimental platform integrates multiple functional modules and constructs a complete control and testing system. In terms of hardware selection, the hardware selection particularly considered the real-time requirements of the system and the compatibility between various components. The core components include three WHEELTEC MG513X DC motors, each equipped with a

Hall encoder to provide precise speed feedback. The attitude measurement adopts the MPU6050 sensor to provide high-precision angle and angular velocity information for the system, as shown in Fig. 7.

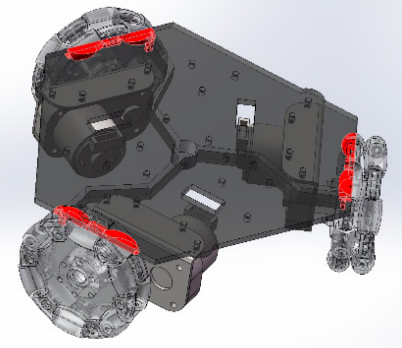

Fig. 7 Platform. (Picture/Photo credit: Original)

The design of the software system adopts a modular architecture, which has the advantage of low coupling between various functional modules, making it easy to debug and maintain. The data acquisition module of the system achieves high-speed communication with MPU6050 through the I2C protocol, and the sampling frequency is set to 400kHz to ensure real-time data. The processing of encoder signals adopts interrupt mode, which achieves x2 frequency doubling and improves the accuracy of speed measurement [6].

The implementation of control algorithms considers real-time requirements, with only necessary calculations retained in the main program loop and complex operations handled in the interrupt service program. Through this method, timely updates of control signals and stable operation of the system are ensured. At the same time, the system also implements an online parameter adjustment function, which facilitates performance optimization in practical applications.

3. Results and Discussions

3.1 Performance Analysis of PID Controller

4.1.1 Steady-state error analysis

Through steady-state performance testing of the system, Results showed that the controller exhibits different characteristics under different operating conditions. In the initial design, when only proportional control is used, there is a significant steady-state error in the system, with an amplitude of 5-10%. This error can cause significant deviations between the actual motion state of the robot and the expected value, seriously affecting the control accuracy.

After in-depth research, it was determined that simple proportional control cannot meet the system's accuracy requirements. By introducing an integral term, the steady-state performance of the system is significantly improved [7]. The optimized PI control reduces the steady-state error to below 1% while maintaining a response time of 200-300ms for the system. This improvement not only improves control accuracy but also maintains the fast response characteristics of the system.

4.1.2 Dynamic response characteristics

The dynamic performance testing of the system mainly focuses on response characteristics and control stability. After extensive experiments, a detailed analysis of the dynamic response of the system under different operating conditions was conducted. The optimized system exhibits excellent dynamic performance, with a rise time of only 150ms, adjustment time controlled within 300ms, and overshoot successfully controlled below 5%, as shown in Fig. 8, through parameter optimization. These indicators meet the requirements of practical applications.

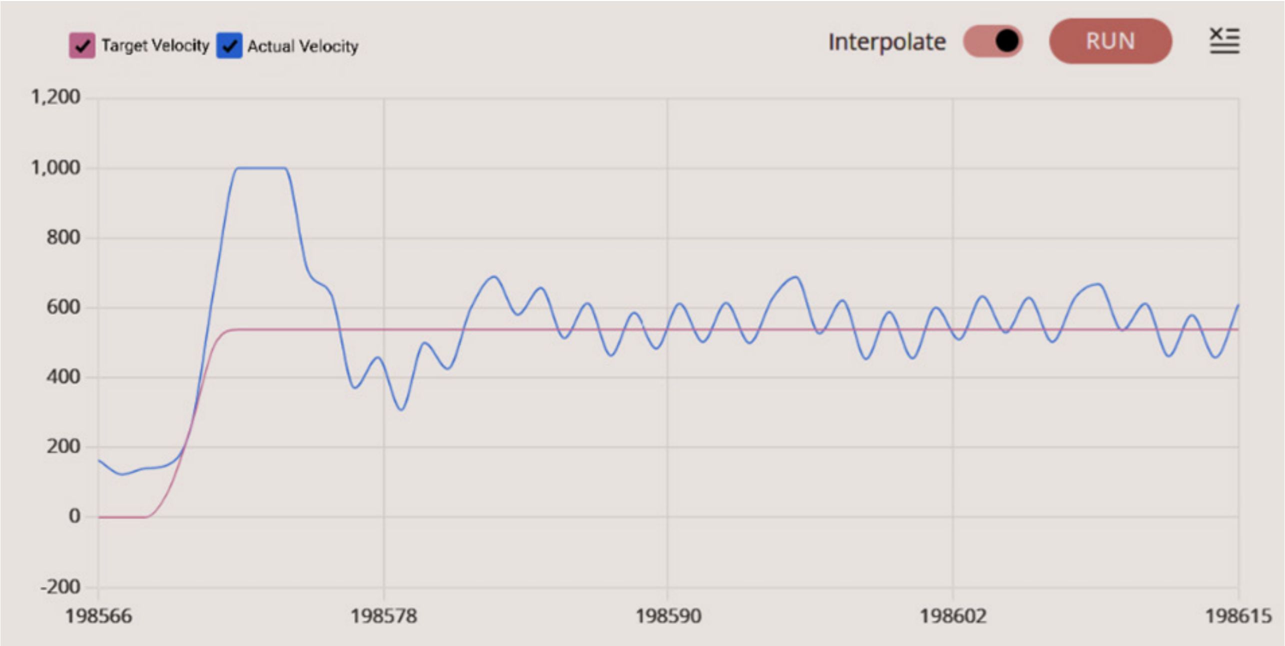

Fig. 8 Response under PI control for velocity loop. (Picture/Photo credit: Original)

In order to improve the dynamic performance of the system further, it incorporates an innovative integral term, the fast decay mechanism, in the speed stage [8]. When the system needs to stop quickly, this mechanism can actively reduce the influence of the integral term, significantly improving the braking performance of the system.

Experimental data shows that this mechanism reduces the system's stop response time by about 40%, greatly improving the flexibility of control.

4.1.3 Assessment of anti-interference capability

In practical application environments, robots face complex and ever-changing external disturbances. Through the anti-interference performance test of the system, Simulation of various possible interference scenarios, including external impact, ground tilt, and load changes are conducted. The test results show that the system exhibits strong anti-interference ability. In the external thrust interference test, the robot can restore balance within 0.5 seconds; In the slope adaptability test, the system can stably adapt to a maximum tilt angle of 15 degrees; In the face of sudden load changes, the control system can complete adjustments and maintain stability within 0.3 seconds.

This excellent anti-interference performance is mainly due to the dual loop control structure and reasonable parameter configuration adopted by the system. The PD control of the inner loop provides fast attitude correction capability, while the PI control of the outer loop ensures the accuracy of motion. The synergistic effect of two control loops enables the system to effectively respond to various external disturbances.

3.2 Parameter optimization and its impact

Optimizing control parameters is a key step in improving system performance. Through systematic experimental research, the experimental research revealed that different parameters have a significant impact on system performance. In the balance control stage, the proportional gain (Kp=40) directly affects the response speed and stability of the system, while the differential gain (Kd=2) suppresses oscillations by providing appropriate damping. The combination of these two parameters plays a decisive role in the dynamic performance of the system.

The optimization of parameters in the speed control process is equally crucial. After repeated testing, The optimal parameter combination was determined: proportional gain Kp-velocity=8, integral gain Ki-velocity=0.2. This set of parameters achieves a good balance between response speed and steady-state accuracy [9]. To prevent integral saturation and system oscillation, the system also incorporates optimization strategies such as integral limiting and low-pass filtering [10].

3.3 Application cases in all terrain robots

The control system developed in this study has been successfully applied on a spherical all-terrain robot platform, as shown in Fig. 9. The platform achieves flexible all-round motion capability through coordinated control of three omnidirectional wheels. In practical application testing, the system has demonstrated excellent comprehensive performance. In terms of flexibility in movement, robots are capable of rotating in place and moving in all directions; In terms of environmental adaptability, the system has successfully adapted to various ground materials and has the ability to cross obstacles with 2cm steps.

The operational convenience of the system has also been fully verified. Through the PS2 wireless controller, the operator can intuitively control the movement of the robot, while monitoring the system status in real time and adjusting control parameters through the OLED display screen. This human-computer interaction design greatly improves the practicality and operability of the system. Through long-term field testing, the system has demonstrated good stability and reliability, fully verifying the effectiveness of the designed control scheme.

The success of these practical applications not only proves the feasibility of the control strategy proposed in this study but also provides valuable references for the development of similar robot platforms. Future research will focus on further improving the system's adaptability and intelligence level to adapt to more complex application scenarios.

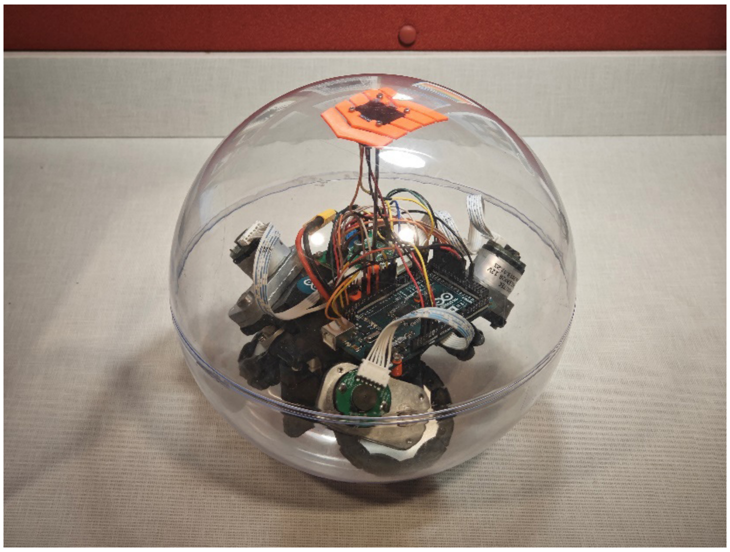

Fig. 9 Self-balancing robot. (Picture/Photo credit: Original)

4. Conclusion

This study proposes and implements a control strategy based on dual-loop PID for the motion control problem of all-terrain robots. Through theoretical analysis and experimental verification, the following main achievements have been achieved:

Firstly, the designed dual loop control system achieves excellent control performance while maintaining a simple structure. The steady-state error of the system is reduced to within 1%, and the dynamic response time is controlled within 150ms, significantly improving the motion accuracy and flexibility of the robot.

Secondly, innovative parameter optimization methods have effectively improved the system's environmental adaptability. The experimental results show that the system can adapt to terrain tilts within 15 degrees, and the recovery time from external disturbances does not exceed 0.5 seconds, demonstrating the robustness and practicality of the control strategy.

Finally, in practical application verification, the system demonstrated all-round motion capability and stable control effect, providing reliable technical support for the development of all-terrain robots.

Future research will focus on improving the adaptive capability of control systems, exploring parameter optimization methods based on machine learning, and further enhancing the system's adaptability in more complex environments. At the same time, the research will be extended to the field of multi-robot collaborative control, providing solutions for a wider range of application scenarios.

References

[1] C. Knospe, PID control, IEEE Control Systems, 2006, 26(1): 30–31.

[2] Y. Li, K. H. Ang, and G. C. Y. Chong, PID control system analysis and design, IEEE Control Systems, 2006, 26(1): 32–41.

[3] N. K. H. Ang, G. Chong, and N. Y. Li, PID control system analysis, design, and technology, IEEE Transactions on Control Systems Technology, 2005, 13(4): 559–576.

[4] K. S. Tang, N. K. F. Man, N. G. Chen, and S. Kwong, An optimal fuzzy PID controller, IEEE Transactions on Industrial Electronics, 2001, 48(4): 757–765.

[5] N. Q. Zhan, N. Y. Cai, and N. C. Yan, Design, analysis and experiments of an omnidirectional spherical robot, IEEE

International Conference on Robotics and Automation, IEEE, 2011, doi: 10.1109/icra.2011.5980491.

[6] M. Seeman, M. Broxvall, A. Saffiotti, and P. Wide, An autonomous spherical robot for security tasks, 2006 IEEE International Conference on Computational Intelligence for Homeland Security and Personal Safety, IEEE, Oct. 2006, doi: 10.1109/cihsps.2006.313312.

[7] M. Mahmud, S. M. A. Motakabber, A. H. M. Z. Alam, and A. N. Nordin, Adaptive PID Controller Using for Speed Control of the BLDC Motor, 2020 IEEE International Conference on Semiconductor Electronics (ICSE), IEEE, Jul. 2020, doi: 10.1109/icse49846.2020.9166883.

[8] J. W. Jung, V. Q. Leu, T. Duc DO, E. K. Kim, and H. H. Choi, Adaptive PID Speed Control Design for Permanent Magnet Synchronous Motor Drives, IEEE Transactions on Power Electronics, 2014, 30(2): pp. 900–908.

[9] H. Wu, W. Su, and Z. Liu, PID controllers: Design and tuning methods, 2014 9th IEEE Conference on Industrial Electronics and Applications, IEEE, pp. 808–813, Jun. 2014, doi: 10.1109/iciea.2014.6931273.

[10] N. Q. G. Wang, N. T. H. Lee, N. H. W. Fung, N. Q. Bi, and N. Y. Zhang, “PID tuning for improved performance,” IEEE Transactions on Control Systems Technology, 1999, 7(4): 457–465.